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STATE-OF-THE-ART RELIABILITY ESTIMATE OF SATURN V PROPULSION SYSTEMS [redacted]

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RM 63TMP-22

GENERAL ELECTRIC COMPANY
SANTA BARBARA
CALIFORNIA

[redacted]

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STATE-OF-THE-ART RELIABILITY ESTIMATE OF SATURN V PROPULSION SYSTEMS (U)

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GENERAL ELECTRIC COMPANY
SANTA BARBARA, CALIFORNIA

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INTRODUCTION

This report presents the results of a reliability prediction study of the propulsion systems for the NASA-MSFC Saturn V vehicle shown in Figure 1. The TEMPO method of combining the failure mode of each component of the subsystems being analyzed was used throughout the study. Since most of the configurations of the subsystems examined are presently in the development phase, this prediction is based upon the current available data and should be considered a preliminary estimate only.

This study was performed in collaboration with the ARINC Research Corporation as an adjunct to the reliability prediction studies pertinent to the various stages comprising the Saturn V Launch Vehicle System, and administered by the Apollo Support Department of the General Electric Company.* The results of TEMPO's specific areas of investigation are presented. These include reliability estimates of the propulsion systems for the S-IC, S-II, and S-IVB stages of the Saturn V vehicle identified in Figure 1.

A review of the flight history of existing ballistic missiles indicates that as the vehicles progress through the developmental flight test program the reliability increases rapidly at first and then approaches an asymptotic value. This asymptotic value of reliability is referred to as "state-of-the-art" reliability,† and it represents the reliability potential after embryonic design failures have been identifield in the flight test program and eliminated.

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*Performance of this contract was conducted under the technical direction of the Saturn Systems Office of NASA's Marshall Space Flight Center and administered by General Electric Purchase Order No. 036-850150-54081 under NASA Contract NASw-410.

†Designated "state-of-art" reliability throughout the remainder of this report.

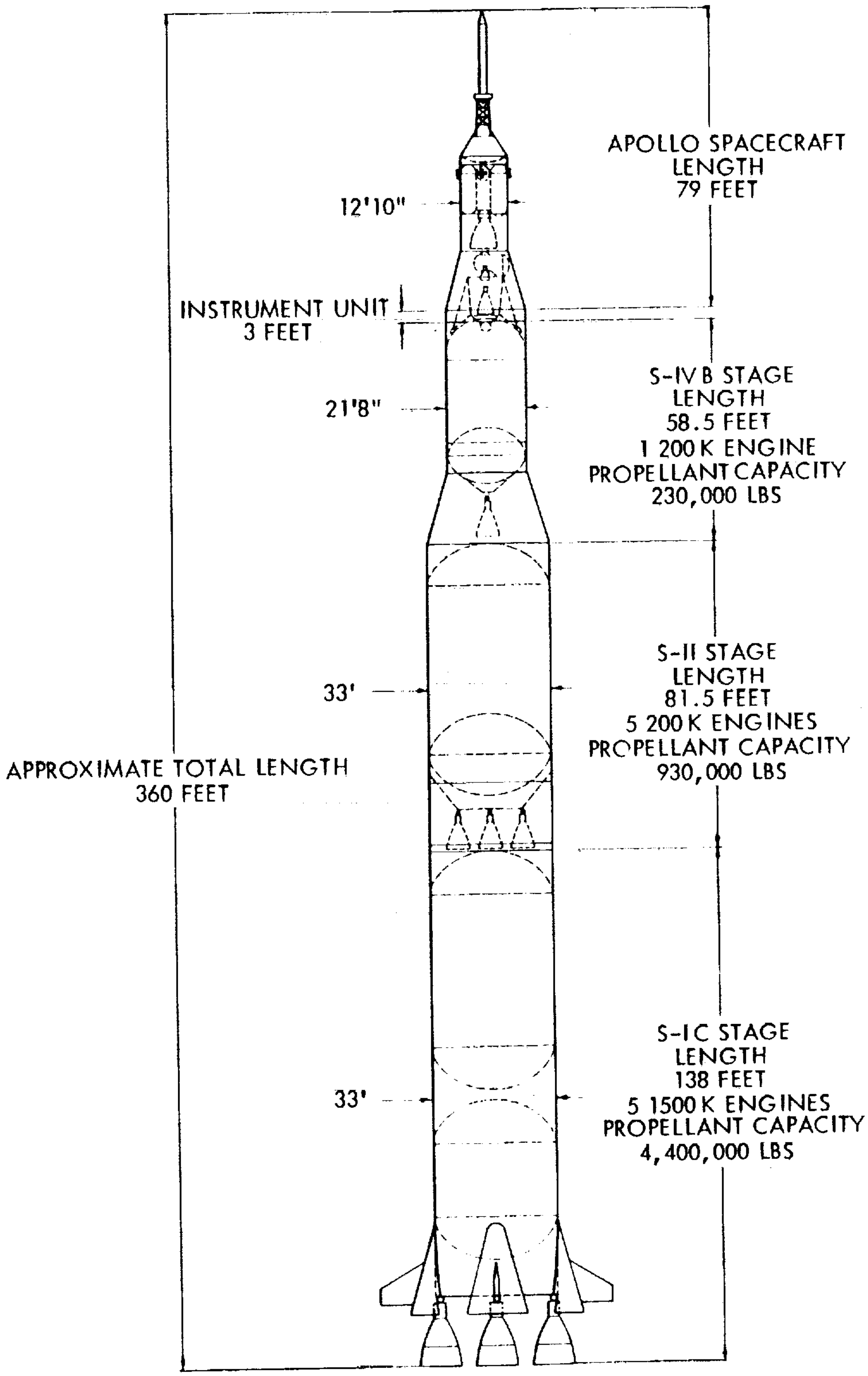

Figure 1. Saturn V vehicle configuration

SECTION I
PROPULSION SYSTEMS RELIABILITY

The leveling off of the predicted state-of-art reliability is due, as the name implies, to the limitations in materials, design, manufacturing, and testing within the bounds of the current technology. The methodology used in predicting the state-of-art reliability for this study is based on the use of propulsion systems component data from liquid propellant rocket engines in advanced phases of development. Thus, the state-of-art estimates presented in this report should reflect the reliability potential of the subject systems within the limitations of the present technology. These estimates do not imply a limitation of the subject system reliability to that predicted, but are intended as a guide indicating what reliability level might reasonably be expected of these systems.

This section describes the method used for prediction of the state-of-art reliability of the propulsion systems for the S-IC, S-II, and S-IVB stages of the Saturn V vehicle. The methodology for evaluating system reliability, as illustrated in Figure 2, required a failure or malfunction analysis of each system to establish the components and subsystems which are vital to its successful operation. Such an analysis is essentially an inventory and examination of the components to determine whether their failure will result in a corresponding failure of the system and, if so, the manner in which the system will fail. The malfunction analysis is used to establish a failure network (or failure mode analysis) for the system which permits overall system reliability to be estimated from component reliabilities.

To facilitate the reliability prediction, each propulsion system was divided into functional equipment systems, each of which operates independently of the others and can thus be analyzed separately. These systems are:

1. Fuel system (includes tankage and associated plumbing required to deliver fuel to the engine system).

2. Oxidizer system (includes tankage and associated plumbing required to deliver oxidizer to the engine system).

3. Hydraulic control system (required for engine gimballing).

4. Control pressure system (supplies an inert gas at ambient temperature for valve actuation).

5. Engine system.

Malfunction and failure mode analyses were performed to determine the reliability of each system. The state-of-art reliability of the propulsion system is obtained from a combination of the reliabilities for all the independent equipment systems.

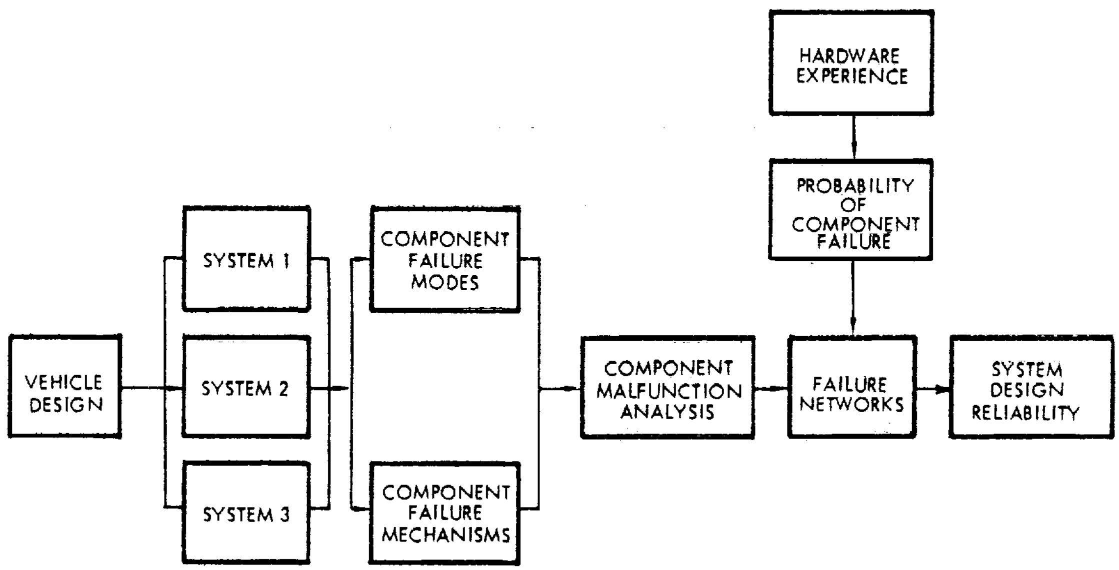

Figure 2. Methodology for establishing system design reliability

SECTION II
COMPONENT RELIABILITY DATA

State-of-art reliability estimates should be required for each phase of a missile systems' development program, from preliminary design through the operational use of the missile. Table 1 outlines the relationship of the reliability and engineering programs for the four phases of a system development program. In the initial developmental phases the state-of-art estimates are the only estimates that can be made since there is no existing system hardware test data available to allow actual systems reliability to be determined. These state-of-art estimates are then the only known source of reliability information based on actual failure data from which initial design assessments and resource allocations can be made. In the later phases of the development program these state-of-art estimates are combined with reliability estimates of the hardware to aid in the assessment of the program and to indicate critical areas. Failure data indicative of the current technological limitations of the subject system in the actual flight operational environment are required in all the phases in order to prepare the state-of-art estimates. In compiling this state-of-art failure data for propulsion and mechanical system components, the following factors were considered:

1. Propulsion system components are operated for only a small fraction of their lifetimes; therefore, operating environment is of greater importance than operating time.

2. In general, propulsion systems fail as the result of the failure of a particular component to operate as required in a particular operational mode (e.g., vent valve fails open, vent valve fails closed, pressure switch fails closed, etc.). The reliability assessment of these systems requires failure data that includes an apportionment of the failures between the component operational modes.

3. Expected operating environments are difficult to anticipate or simulate. For this reason, the best failure data are obtained from flight test results.

Table 1. Objectives and tests of a reliability-engineering program

	RELIABILITY PROGRAM	ENGINEERING PROGRAM
PHASE I Objectives:	Synthesis (malfunction analysis) (1) Early recognition of failure modes and problem areas (2) Permits early recognition of product maturity (3) Evaluation and recommendation of design modifications (4) Test planning	Design (1) System specifications and drawings (2) Test planning
Type of tests:		(1) Feasibility tests
PHASE II Objectives:	Attainment (1) Identify failure mechanisms (2) Identify failure modes	Development (1) Establish proper system functioning under limited environment
Type of tests:	(1) Induced malfunction tests (2) Tests-to-failure (limit tests, endurance tests)	(1) Functional test, limited environment (Qualification and PFRT tests)
PHASE III Objectives:	Demonstration (1) To establish probability that all required failure mechanisms have been located and eliminated	Operation (1) To obtain proper system functioning under actual environment (includes human factors and flight)
Type of tests:	(1) All type tests provide information (2) Confidence tests	(1) Functional tests—actual environment (Qualification)
PHASE IV Objectives:	Maintenance (1) To maintain system reliability throughout the operational use of the system	Production (1) To obtain proper system functioning under production conditions
Type of tests:	(1) Aging tests (2) Surveillance tests (3) Reliability verification tests*	(1) Functional tests (acceptance tests) (2) Quality verification tests*

*Rocketdyne nomenclature.

Unfortunately, missile flight data cannot be relied upon to supply sufficient information for establishing component reliability values because the number of test flights is small and the monitoring of all components is not feasible. The component data that are available from missile flight programs are primarily maintenance data; that is, tabulations of component failure modes and failure mechanisms which have occurred in the checkout of the missiles. Such data are useful in identifying component failure mechanisms and their relative rates of occurrence, but they do not provide the basis for establishing the frequency of failures under conditions that exist in flight. However, the missile flight programs, while not a source of component failure data, do provide failure data on the major subsystems.

Nearly 10,000 well monitored runs on hot-fire test stands have been made over the past five years on large liquid propellant rocket engines. The environment to which the components are exposed in these firings simulates the actual flight environment. The component failure data from the test stand runs include both maintenance and cutoff failures from engine systems in advance phase of development. During a test maintenance failures may occur that do not necessarily result in premature shutdown, but may necessitate corrective maintenance before a specific test can be performed. Cutoff failures that occur during a test result in premature shutdown and closely represent actual failures in flight. The types of failure represented by the cutoff data are those to be expected from components which are fully developed and which have been properly inspected before use. These cutoff stand components failure data, in conjunction with the missile flight major subsytem failure data, were used to obtain the propulsion system component state-of-art reliability estimates used in this study and presented in Table 2.

To permit the data to be used for computing reliability estimates of components in equipment systems other than the engine system, and to average out the effects of design and environment, the failure rates were organized into generalized groupings of components, such as solenoid-actuated valves, pressure switches, etc. Because of the high reliabilities exhibited by the components and the limited number of tests, the generalized groupings were required, in many instances, tc obtain minimal, statistically-significant, reliability estimates.

In order to indicate the relative reliability values of particular vehicle designs, consideration must be given to differences in the manner in which the vehicles are operated. Different modes of operation are particularly apparent in a comparison of: (1) a boost vehicle

Table 2. Propulsion system component reliability estimates (Revised May 1963)

COMPONENT		Observed Reliability All Failures	Failure Distribution per Ref. 1			*APPORTIONED RELIABILITY			
			Start (0–3 sec)	Run Rel.*	(3 sec–) λ	Failure Mode	Start	Run	Shut Down
Main Fuel Valve (Pneu. or hyd. actuated)		.9998	.9998	1.0	.00042	Fail open Fail closed	1.0 .9998	1.0 1.0	1.0 1.0
Main LOX Valve (Pneu. or hyd. actuated)		.9990	.9996	.9994	.012	Fail open Fail closed	.9998 .9996	.9998 .9998	.9998 .9998
Pilot or Control Valve (Pneu. or hyd. actuated)		.9993	.9995	.9998	.0065	Fail open Fail closed	.9999 .9995	.9999 .9999	.9999 .9999
Solenoid Valve		.9996	.9998	.9998	.0060	Fail open Fail closed	.9999 .9999	.9999 .9999	.9999 .9999
Vent or Relief Valve (Spring loaded)		.9998	1.0	.9998	.0052	Fail open Fail closed	1.0 1.0	.9999 .9999	1.0 1.0
Check Valve		>.9999	1.0	>.9999	>.0021	Fail open Fail closed	1.0 —	.9999 —	1.0 —
Servo Valve		>.9995	1.0	>.9994	>.0092	Fail	1.0	.9995	1.0
Pressure Switch		.9991	.9996	.9995	.013	Fail when req'd. Open when not req'd.	.9996 .9998	.9998 .9998	.9998 .9998
Pressure Regulators	LOX	.9978	.9990	.9988	.026	Fail high Fail low	.9995 .9995	.9994 .9994	1.0 1.0
	Non Cryogenic	.9993	.9997	.9996	.0080	Fail high Fail low	.9999 .9999	.9998 .9998	1.0 1.0
Large Thrust Chambers (60K to 200K)		.9975	.9998	.9977	.052	Burn thru, leak, etc.	.9998	.9977	1.0
		.9973	.9995	.9978	.048	Combustion instability	.9995	.9978	1.0
		.9948	.9992	.9956	.098	All failures	.9992	.9956	1.0
Vernier Thrust Chambers		.9995	1.0	.9995	.010	All failures	1.0	.9995	1.0
Gas Generators		.9988	.9992	.9996	.0086	All failures	.9992	.9996	1.0
Turbopump		.9985	.9999	.9986	.032	All failures	.9999	.9996	1.0
Heat Exchangers		.9997	1.0	.9997	.0070	All failures	1.0	.9997	1.0
Tubes, Fittings, Hardware, etc.		.9981	.9999	.9982	.039	Excessive leakage	.9999	.9982	1.0
Misc. Electrical Cable, Fittings, etc.		.9998	1.0	.9998	.0038	All failures	1.0	.9998	1.0
Engine Relay Box (10 relays)		.9983	.9992	.9991	.023	All failures	.9992	.9991	1.0
T.C. & G.G. Ignitors		.9982	.9982	—	—	No ignition	.9982	—	—
Hypergol Ignitors		.9995	.9995	—	—	No ignition	.9995	—	—
Tube Pump		.9988	1.0	.9988	.027	All failures	1.0	.9988	1.0

*For nominal 160 second run time.

which is released from the launch pad after engine ignition and an initial hold-down phase; (2) an upper stage vehicle such as the S-II which is ignited in flight with no hold-down; and (3) the S-IVB stage which may be ignited and shut down more than once in a single mission.

The various vehicle operating modes that are possible can be considered to be different combinations of three operating phases: a starting phase, a running or operating phase, and a shutdown phase. For the purposes of the propulsion system reliability analysis, the operating modes of the Saturn V stages were assigned to these three phases as follows:

1. Start - The phase of operation beginning with the initiation of the engine start cycle (including cool-down of the S-II and S-IVB stages) and extending until 3 seconds after full main engine thrust has been attained.

2. Run - The principal operating phase, beginning with the end of the start phase and continuing until the initiation of the shutdown phase.

3. Shutdown - The phase of operation beginning with the initiation of engine shutdown and proceeding until complete termination of thrust has been attained.

The apportionment of the component failure data into the three operating phases was based on data furnished by Rocktdyne[1] and indicates the distribution of cutoff failures between ignition plus 3 seconds of full thrust (start phase) and the full duration, full thrust operation (run phase) for the Atlas booster and sustainer, Thor, and H-1 engines. The apportionment of the data into failure modes or phases not described in the Rocketdyne data was made by considering either of the modes of failure in question as equally likely to happen (fail open is as likely as fail closed).

A main oxidizer valve can be used as an example. Since this valve failing open during the start phase would not be apparent until shutdown, this failure would not be recorded as a start phase failure. Thus all the failures indicated for the start phase must be due to the valve failing closed. The remaining, or run phase, portion of the valve failure probability was then equally apportioned between the other phases and modes included in the cutoff failure data (fail open during the start, run or shutdown phases, or fail closed during the run phase). The probability of failing closed during the shutdown phase, which was not included in the cutoff data, was then considered to exhibit the same reliability as during the start and run phases. Other component reliability estimates were apportioned in a similar manner.

The component failure rate estimates listed in Table 2 were made by:

1. Assuming rocket engine components exhibit a constant failure rate with time after the starting transients are eliminated,

2. Weighting, or apportioning, of the failures between the various components by using the hot fire test stand data (e.g., determining a solenoid valve is X times more reliable than a turbopump), and

3. Assuming the ratio of inflight-failure-rate to test-stand-failure-rate of the engine system components is the same as that exhibited by the complete engine system.

An analysis of hot fire engine test stand data[2] indicates that, during the steady state operation of the engine (run phase), the engine failure rate is constant with time. The failure rate is constant because:

1. The components used on the engines for the hot fire stand tests are all debugged and checked out before use and the only hot fire engine tests considered were for engines in advanced stages of development.

2. The engines and/or engine components used in the hot fire tests are replaced before wearout becomes a factor.

Finally, it should be noted that in a past study[3] performed by TEMPO personnel, close correlation between actual missile flight subsystem failure data and the test stand component failure data was obtained by comparing the former with state-of-art estimates made for the same systems using the test stand component failure data in Table 2.

SECTION III

FAILURE ANALYSIS RESULTS

Figure 3 is a block diagram of the S-II or S-IVB propulsion system. The S-IC propulsion system is similar except that no "chill down" is required. Reliability estimates are made for the systems NEOC (no engine-out capability) and SEOC (single engine-out capability).

Distinction between safe shutdown and catastrophic failure of an engine has been made in these estimates. The safe shutdown (SSD) mode does not in itself imply "engine out" capability but does prevent engine destruction of the stage and the resulting immediate abort. The SSD mode actually allows an alternate mission capability and increased manned safety including a time delay for aborts.

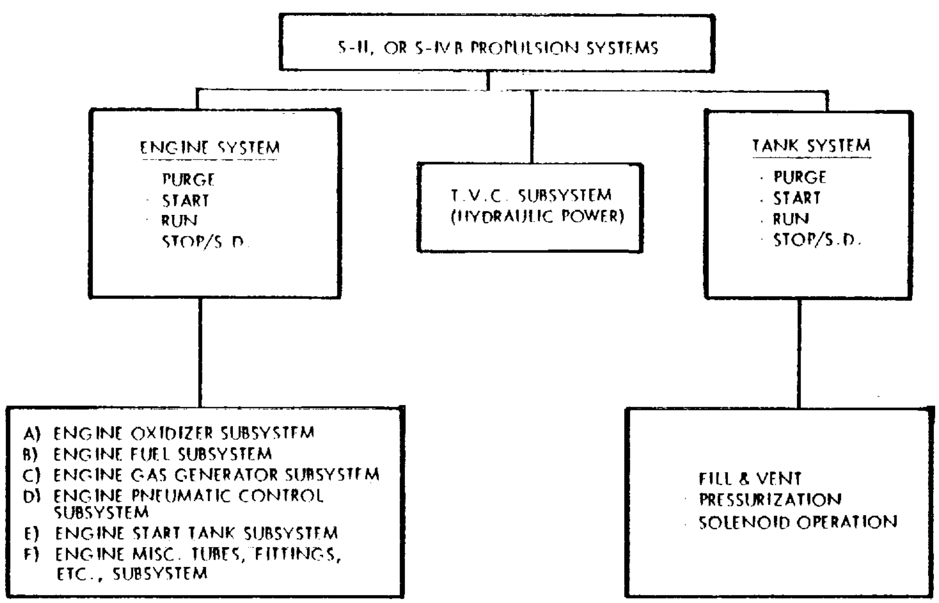

Figure 3. Block diagram of J-2 propulsion system

Figures 4 through 11 in the pages which follow present simplified schematics of the following equipment systems which comprise the propulsion systems of the Saturn V vehicle:

1. F-1 engine of S-IC stage
2. S-IC stage fuel system
3. S-IC stage oxidizer system
4. S-IC stage control pressure system
5. J-2 engine
6. S-II stage hydraulic system
7. S-IVB stage hydraulic system
8. S-II and S-IVB stages tank and propellant feed system.

Tables 3 through 10 which follow the illustrations are "short form" failure analysis charts for the systems listed above. The short form is a simplified first estimate malfunction analysis in which redundant failure modes are not considered since the analysis covers only major considerations. Each system is considered for the various phases of operation: purge, chill down (when required), engine start, run, and shutdown (when a restart is required), or stop (when a restart is not required).

Figure 12 is a plot of the reliability of the cluster (number of successful stage operations before a failure) versus the single engine reliability for a cluster of five F-1 or five J-2 engines, four of which are gimballed. The graph is based on the concepts presented in the TEMPO report[3] on Saturn C-I "Engine-Out Study," performed for NASA. The five curves take into account the thrust vector control (TVC) system and the sensor system.

The TVC system reliability is based on the following equation:

$$P_v = 1 - 0.1\ (1 - P_{e0})$$

where P_{e0} is the total engine reliability and P_v is the TVC system reliability in the catastrophic failure mode.

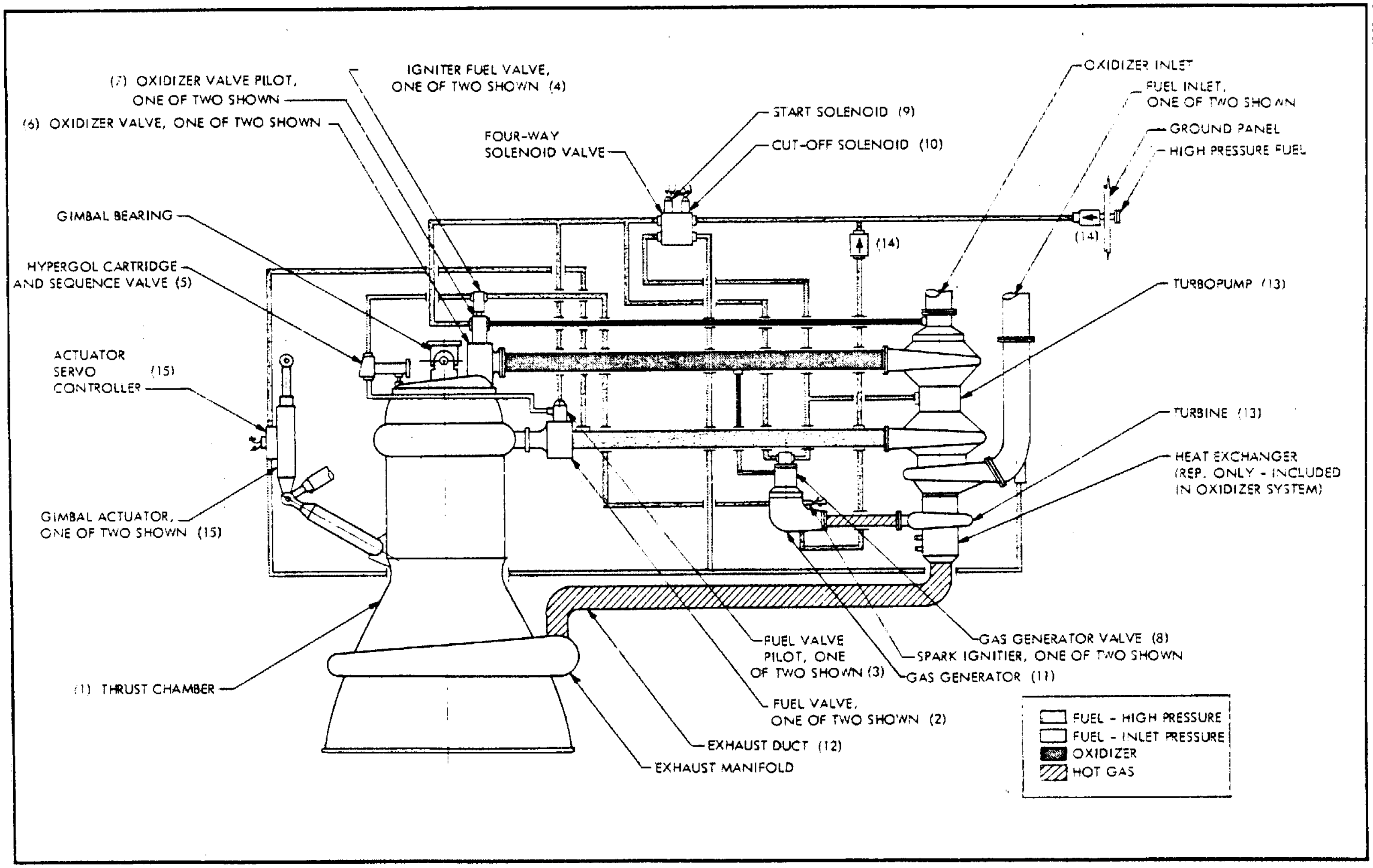

Figure 4. F-1 engine schematic S-IC stage single engine subsystem

Table 3.

FAILURE ANALYSIS CHART FOR: S-IC STAGE OF SATURN V VEHICLE

SYSTEM: F-1 SINGLE ENGINE SUBSYSTEM

STATE-OF-THE-ART RELIABILITY ESTIMATE

SYSTEM FAILURE MODES:
0. ALL FAILURES
1. ALL ENGINES FAIL
2. SINGLE ENGINE FAILURE
3. GUIDANCE FAILURE
4. CATASTROPHIC EXPLOSION

COMPONENT	FIND NUMBER	COMPONENT FAILURE MODE	REFERENCE NUMBER	EFFECT OF COMPONENT FAILURE MODE	ULTIMATE SYSTEM FAILURE MODE	FAILURE PROBABILITY ASSIGNABLE TO EACH OPERATING PHASE ($X10^{-4}$) START	RUN	SHUT DOWN
Thrust Chamber	1	Combustion instability, injector failure, burn through, etc.	1		2, 4		44	
Main Fuel Valve (Any of two)	2	Fail open	2		0		0	
		Fail closed	3		2		0	
Fuel Pilot Valve (Any of two)	3	Fail open	4		0		(2)1	
		Fail closed	5		2		(2)1	
Igniter Fuel Valve (Either of two)	4	Fail open	6	Valves are redundant	0		0	
		Fail closed	7		0		(2)1	
Sequence Valve	5	Fail open	8		0		1	
		Fail closed	9		2		1	
Main Oxidizer Valve (Either of two)	6	Fail open	10		0		(2)2	
		Fail closed	11		2		(2)2	
Oxidizer Pilot Valve (Either of two)	7	Fail open	12		0		(2)1	
		Fail closed	13		2		(2)1	
Gas Generator Valve	8	Fail open	14		0		2	
		Fail closed	15		2		2	
Four-way Solenoid Start Solenoid	9	Fail open	16		0		1	
		Fail closed	17		3		1	
Four-way Solenoid Cut-off Solenoid	10	Fail open	18		2		1	
		Fail closed	19		3		1	
Gas Generator	11	Combustion instability, injector failure, burn through, etc.	20		2		4	
Exhaust Duct and Manifold	12	Rupture or burn through	21		2		2	
Tubes, fittings, Lines and Gaskets		Rupture or excessive leakage	22		2		18	
Turbopump Assembly	13	Mechanical failure	23		2		14	
Check Valves (Either of two)	14	Fail open	24		2		(2)1	
		Fail closed	25		0		0	
					TOTAL		98	

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Table 3. (Cont'd)

FAILURE ANALYSIS CHART FOR: S-IC STAGE OF SATURN V VEHICLE

SYSTEM: F-1 Engine (continued)

SYSTEM FAILURE MODES:
0. ALL FAILURES
1. ALL ENGINES FAIL
2. SINGLE ENGINE FAILURE
3. GUIDANCE FAILURE
4. CATASTROPHIC EXPLOSION

COMPONENT	FIND NUMBER	COMPONENT FAILURE MODE	REFERENCE NUMBER	EFFECT OF COMPONENT FAILURE MODE	ULTIMATE SYSTEM FAILURE MODE	FAILURE PROBABILITY ASSIGNABLE TO EACH OPERATING PHASE p x 10^{-4} START	RUN	SHUT DOWN
F-1 SINGLE ENGINE SUBSYSTEM RUN RELIABILITY = .9902								
		INTEGRAL HYDRAULIC SYSTEM (T. V. C.)						
Gimbal Actuator Lines and Fittings		Rupture or excessive leakage	26		3		3	
Gimbal Actuator and Servo (Either of two)	15	All failures	27		3		(2)5	
					TOTAL		13	

SINGLE ENGINE HYDRAULIC SUBSYSTEM RELIABILITY = .9987

NOTE: The component reliability estimates given here are based on failure data obtained from current LOX-RP1 propellant large rocket engines.

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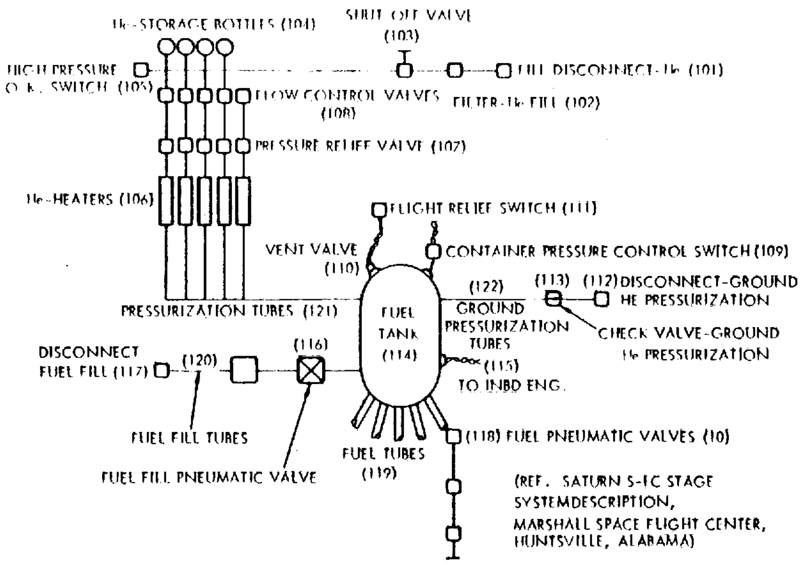


Figure 5. S-IC stage fuel system

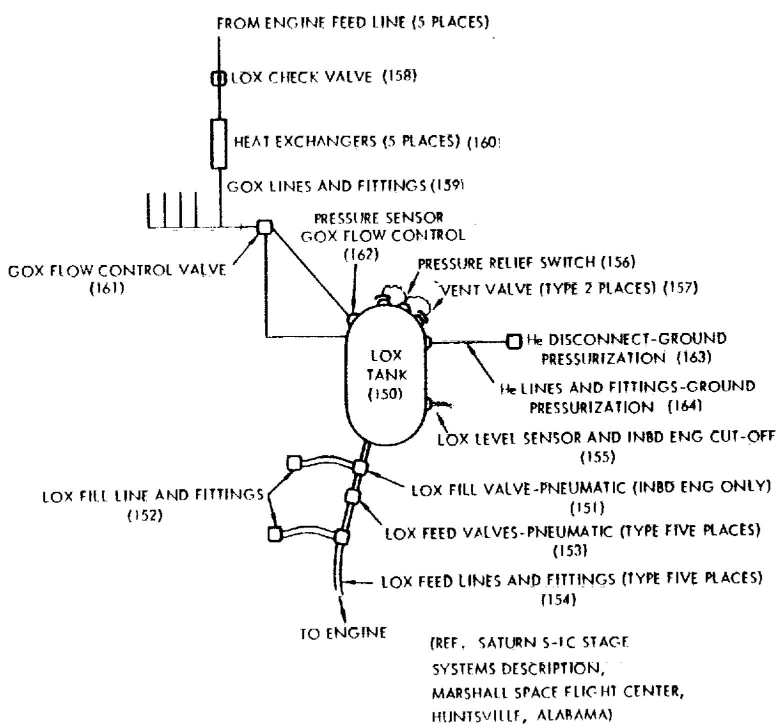


Figure 6. S-IC stage oxidizer system of Saturn V vehicle

Table 4.

FAILURE ANALYSIS CHART (SHORT FORM) FOR: S-IC STAGE OF SATURN V VEHICLE

SYSTEM: FUEL SYSTEM
STATE-OF-THE-ART RELIABILITY ESTIMATE

SYSTEM FAILURE MODES:
0. NO FAILURE
1. ALL ENGINES FAIL
2. SINGLE ENGINE FAILURE
3. GUIDANCE FAILURE
4. CATASTROPHIC EXPLOSION

COMPONENT	FIND NUMBER	COMPONENT FAILURE MODE	REFERENCE NUMBER	EFFECT OF COMPONENT FAILURE MODE	ULTIMATE SYSTEM FAILURE MODE	FAILURE PROBABILITY ASSIGNABLE TO EACH OPERATING PHASE: START	RUN	SHUT DOWN
Disconnect-helium fill.	101	Excess leakage; or fails open.	1		0, 1		1.0	-
Filter-helium fill.	102	Plugs; excess leakage.	2		0		1.0	
Shut-off valve helium fill.	103	Fails open.	3		1		.9999	
		Fails closed.	4		0		.9999	
Helium storage bottles (4).	104	Ruptures; or outlet plugs.	5		1		1.0	
High pressure O.K. switch-helium.	105	Fails to come on at 3050 psig.	6		1		.9998	
		Fails to go off at less than 2850 psig.	7		1		.9998	
Helium heat exchangers F-1 engines (5) (any of five).	106	Rupture or burnout of interface, loss of turbine exhaust flow or loss at helium flow.	8		1		.9987	
Pressure relief valve-He manifold.	107	Fail open in flight.	9		1		.9999	
		Fail closed in flight.	10		1		.9999	
Flow control valves-Helium (5) (any of five).	108	Fail open.	11		1		.9995	
		Fail closed.	12		1		.9995	
Container pressure control switch.	109	Fails to indicate overpressure or indicates overpressure when none occurs.	13	Redundant with vent valve (110).	1		.9998	
Vent valve-fuel tank.	110	Fails open.	14		1		.9999	
		Fails closed.	15	Redundant with (111).	4		.9999	
Flight relief switch.	111	Fails to indicate overpressure.	16	Redundant with (110).	4		.9999	
		False indication of overpressure.	17		1		.9998	
Disconnect-ground He pressurization.	112	Excess leakage.	18		0		1.0	
Check valve-ground He pressurization.	113	Fails open.	19		0		.9999	
		Fails closed	20		0		.9999	
Fuel tank.	114	Leakage; or rupture.	21		1, 4		1.0	
Fuel level-sensor	115	Indicates level inaccurately.	22		1		.9998	
Pneumatic valve-fuel fill.	116	Fail open.	23		0		1.0	
		Fail closed.	24		0		1.0	
Disconnect - Fuel fill	117	Excess leakage.	25		0		1.0	
Pneumatic valves fuel feed (10).	118	Fail open.	26		2		1.0	
		Fail closed.	27		2		1.0	
Fuel Feed Lines 12" diameter (10).	119	Excessive leakage	28		2, 4		.9997	
Fuel fill lines (1).	120	Excessive leakage.	29		0		.9997	
High Pressure-He Tubing.	121	Excessive leakage.	30		1		.9997	
High Pressure-He Tubing Ground Supply.	122	Excessive leakage.	31		0		.9997	
		SYSTEM RELIABILITY		= .9956				

Table 5.

FAILURE ANALYSIS CHART (SHORT FORM) FOR: S-IC Stage of Saturn V Vehicle

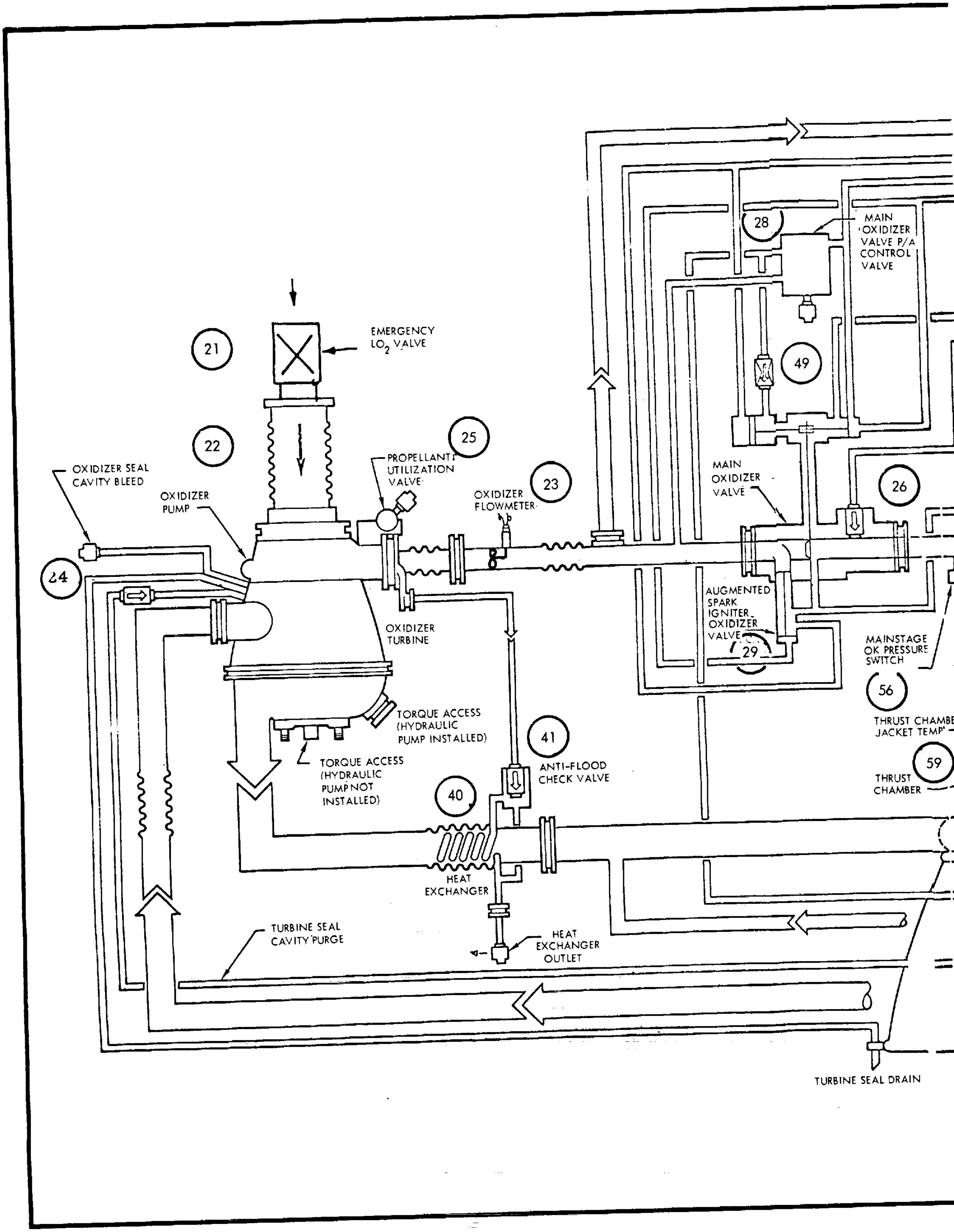
SYSTEM: Oxidizer System
State of the Art Reliability
Estimate

SYSTEM FAILURE MODES:
0. No Failure
1. ALL ENGINES FAIL
2. SINGLE ENGINE FAILURE
3. GUIDANCE FAILURE
4. CATASTROPHIC EXPLOSION

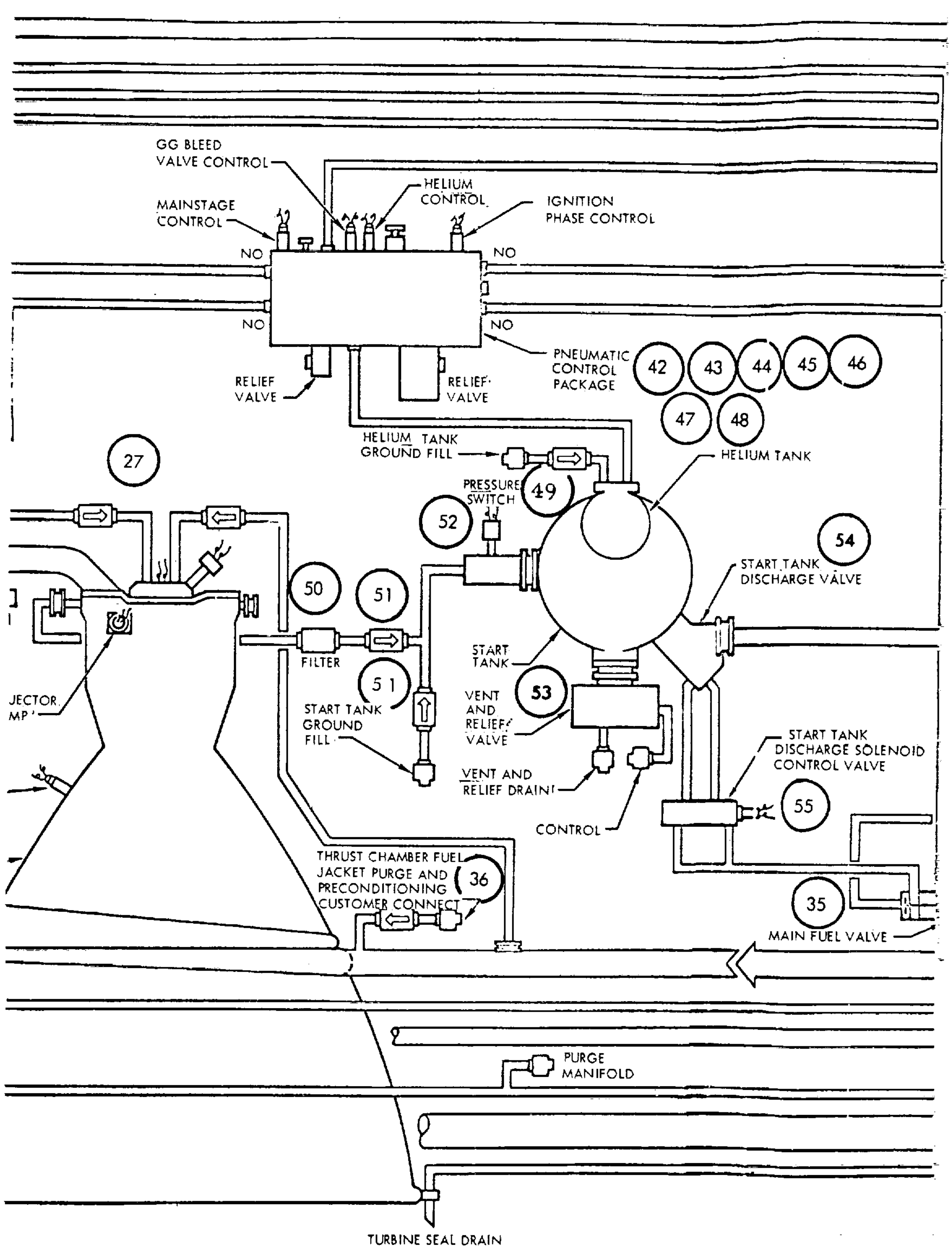
COMPONENT	FIND NUMBER	COMPONENT FAILURE MODE	REFERENCE NUMBER	EFFECT OF COMPONENT FAILURE MODE	ULTIMATE SYSTEM FAILURE MODE	FAILURE PROBABILITY ASSIGNABLE TO EACH OPERATING PHASE: START	RUN	SHUT DOWN
LOX tank	150	Excess leakage or rupture	1		2, 4		1.0	
LOX fill valve - pneumatic (either of two)	151	Fails open	2		1		.9996	
		Fails closed	3		0		.9996	
LOX fill lines & fittings (either of two)	152	Excess leakage or rupture	4		0		.9994	
LOX feed valves (any of five)	153	Fail open	5		0		.9990	
		Fail closed	6		1		.9990	
LOX feed lines & fittings (any of five)	154	Excess leakage or rupture	7		1		.9985	
LOX level sensor	155	Inaccurate level indication	8		1, 2		.9998	
Pressure relief switch LOX tank	156	Fails on; when should be off	9	Redundant with vent valves	1		.9998	
		Fails off; when should be on	10	Redundant with vent valves	4		.9998	
Vent - Relief	157	Fails open	11	Redundant with pressure switch	1		.9999	
Valve LOX tank (either of two)		Fails closed	12		4		.9999	
LOX check valve (any of five)	158	Fails open	13		1		.9995	
		Fails closed	14		0		1.0	
GOX lines and fittings	159	Excess leakage or rupture	15		1		.9997	
Heat exchangers (any of five)	160	Burn through or loss of GOX or turbine gas glow	16		1		.9985	
GOX flow control valve	161	Fail open	17		1		.9999	
		Fail closed	18		1		.9999	
Pressure sensor-GOX flow control	162	Inaccurate indication of LOX tank pressure	19		1, 4		.9998	
He - ground pressurization disconnect	163	Fail open	20		1		1.0	
		Fail closed	21		0		1.0	
He - ground pressurization lines	164	Excess leakage or rupture			0		.9997	

SYSTEM RELIABILITY = .9931

FOLDOUT FRAME 1



FOLDOUT FRAME 2



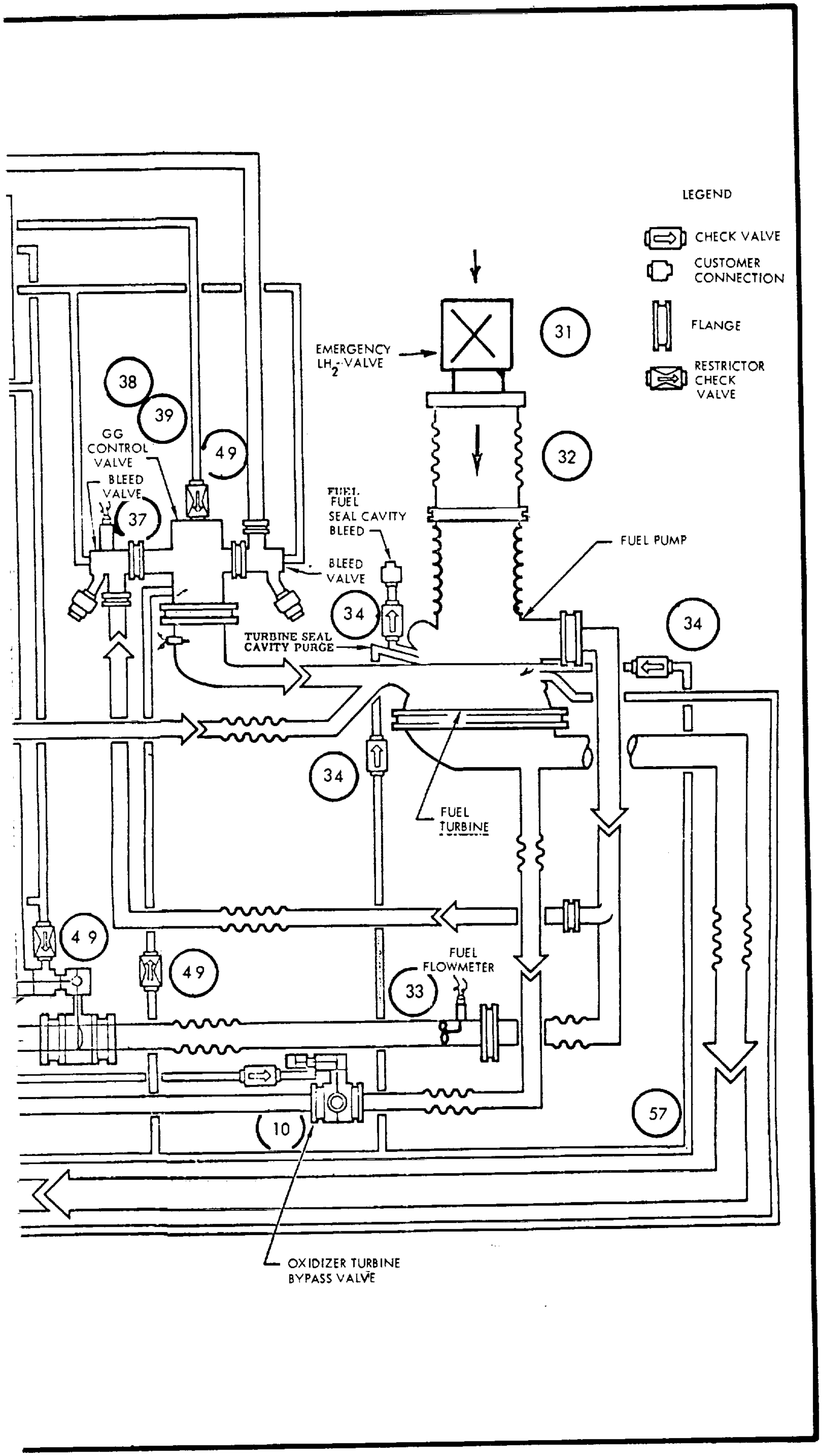


Figure 7. J-2 Engine system schematic

Table 6.

FAILURE ANALYSIS CHART FOR: J-2 ENGINE SYSTEM

SYSTEM: a) Engine Oxidizer Subsystem

COMPONENT	FIND NUMBER	COMPONENT FAILURE MODE	REFERENCE NUMBER	EFFECT OF COMPONENT FAILURE MODE	PRE START (CHILL-DOWN)	FAILURE PROBABILITY ASSIGNABLE TO EACH OPERATING PHASE p x 10^4 START	RUN	SHUT DOWN S-II	SHUT DOWN S-IVB
a) Engine Oxidizer Subsystem:									
Emergency shut off oxidizer valve and pressure relief vent	21	Fails to remain open, or closes prematurely.		Engine operation terminated (SSD).	0	4	2	0	2
(SL. ;G, Sg., N. O.) (see code)		Pressure relief vent fails. Fails open, when commanded to close.		Probable engine destruction.	0	(2)	(2)	0	(2)
LO_2 Turbopump	22	During GH_2 startup, and expiration of mainstage timer; during mainstage operation--		Engine operation terminated (SSD)	0	1	14	0	0
		Contamination		Fires, explosions.	0	0	(2)	0	0
LO_2 Flowmeter	23	Bearing function, or contamination		Fires, explosions.	0	0	(1)	0	0
O_2 turbopump seal cavity purge bleed check valve.	24	Leaks, or fails to close, fails to open.		Contamination, ox pump freeze-up—	1	0	1	0	0
(SL, P, Hy, N. C.)				possible damage, fire hazard.	(1)	0	(1)	0	0
LO_2 Propellant Utilization Valve	25	Fails to operate (normal position).		Probability of inefficient use of propellants.	0	0	1	0	0
		Fails to operate (extreme position).		" " "	0	0	1	0	0
(V. F., SM, NO,)		PU valve not in normal position during start or shut down.		Engine start not achieved. Pump stalls.	1	1	0	0	1
Main LO_2 (MOV) valve	26	Fails to open, (FC).		Engine cut off (SSD)	0	4	2	0	2
(SL., G, two-stage operation, Pn, N. C.,)		Fails to close, (FO).		Possible stage separation problems.	0	0	0	1	2
Sequencer valve of main LO_2 valve (pneumatic)	27	Fails to open, (FC).		Engine cut off (SSD).	0	5	0	0	0
(3 way-Pn-mech-linked to MOV)		Fails to close, (FO).		May result in Ox rich cut off T/C damage and Ox drainage.	0	0	1	0	1
Pressure Actuator control valve of main LO_2 valve (3 way-Pn-)	28	Fails to open.		Engine C/O by mainstage timer (SSD).	0	5	0	0	0
		Premature opening or locked in open position, cannot close at C/O.		Fuel pump stall, over-temp. due to LOX rich condition.	0	2	2	0	2

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Table 6. (Cont'd)

FAILURE ANALYSIS CHART FOR: J-2 ENGINE SYSTEM (continued).

SYSTEM: b) Engine Fuel Subsystem.

COMPONENT	FIND NUMBER	COMPONENT FAILURE MODE	REFERENCE NUMBER	EFFECT OF COMPONENT FAILURE MODE	CHILL DOWN	FAILURE PROBABILITY ASSIGNABLE TO EACH OPERATING PHASE: START	RUN	SHUT DOWN: S-II	S-IVB
ASI- Augmented spark igniter oxidizer valves. (P, Pn, NC)	29	Fails to open.		May result in hard start or detonation.	0	1	(1)	0	1
		Fails to close.							
Oxidizer turbine bi-pass valve. (SL; G, N. O.)	30	Fails closed, fails to open after cut off.		No restart fuel pump stall.	0	1	1	0	1
		Fails open (fails to close during start)		Excessive GG by-pass - low perf.	0	2	0	0	1
b) Engine Fuel Subsystem:									
Emergency shut-off fuel valve (S. L; G, Sq, N. O.)	31	Fails to remain open, or closes prematurely.		Engine operation terminated (SSD).	0	4	2	0	2
		Fails open, when commanded to close.		Engine destruction	0	(2)	(2)	0	(2)
LH_2 Turbo pump	32	Failure during GH_2 startup, and expiration of mainstage timer; during mainstage operation.		Engine operation terminated (SSD).	0	1	14	0	0
LH_2 Flow meter	33	Fails		Probable, will not affect operation.	0	0	0	0	0
H_2 turbo pump seal cavity purge and bleed system. 3 req'd.	34	Leaks or fails to close.		Pump freeze-up failure.	2	0	2	0	0
		Fails to open.		Fire hazard	(2)	0	(2)	0	0
Main fuel valve (MFV) (Two position; G, Pn)	35	Fails to open fully.		No engine start (SSD)	0	2	0	0	1
		Fails to close (FO).		No effect, except for re-start.	0	0	0	0	1
Thrust chamber fuel jacket purge and preconditioning connect.	36	Fails closed.		Prevents purge operation, may cause hard start due to improper chill down.	1	0	0	0	0
		Fails open.		Prevents past firing purge.	0	0	0	0	1

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Table 6. (Cont'd)

page 3

FAILURE ANALYSIS CHART FOR: J-2 ENGINE SYSTEM (continued).

SYSTEM: c) Engine Gas Generator Subsystem.
d) Engine Pneumatic Control Package Subsystem.

COMPONENT	FIND NUMBER	COMPONENT FAILURE MODE	REFERENCE NUMBER	EFFECT OF COMPONENT FAILURE MODE	CHILL DOWN	FAILURE PROBABILITY ASSIGNABLE TO EACH OPERATING PHASE: START	RUN	SHUT DOWN S-II	SHUT DOWN S-IVB
c) Engine Gas Generator Subsystem:									
G. G. {O_2 / H_2} bleed valve mechanically linked. (P, Pn, N. C.).	37	Fails to open.		Engine cut off (SSD).	0	1	1	0	1
		Fails to close.		G. G. burnout fire hazard.	0	5	1	1	1
G. G. Solenoid control valve.	38	Fails open.		Engine will not bootstrap (SSD).	0	1	1	0	1
(3 position, P, Sd, N. C.)		Fails closed.		Engine cannot start.	0	1	1	0	1
G. G. Injector assembly	39	All failures.		SSD	0	7	3	0	1
				Detonations, fires.	0	(1)	(1)	0	0
Heat exchanger assembly.	40	All failures.			0	0	3	0	0
Heat exchanger anti-flood check valve (Ox.)	41	Fails.			0	0	1	0	0
d) Engine Pneumatic Control Package Subsystem:									
Control Valve 4-way, P, Sol, bias to keep MFV, MOV, GGV, closed. 1) Ignition Phase	42a	Fails to actuate when energized.		No engine start.	0	1	1	1	1
		Fails to close when deenergized.		Fuel rich cut off.	0	0	0	0	1
2) Main stage operation phase.	42b	Fails to actuate when energized.		No engine start at expiration of main stage timer.	0	1	1	1	1
•		Fails to close when deenergized.		MOV & GGV will not close, O_2 rich cut off GG & TC burn out.	0	0	0	1	1
G. G. bleed valve control Solenoid valve	43	Fails open.		See gas gen. subsystem. (37)	0	1	1	1	1
		Fails closed.			0	1	1	0	1
Helium control	44	Fails open.		No restart capability. (SSD)	0	1	0	0	1
		Fails closed.			0	1	1	1	1
Two-vent port check valves	45	Fails open.		No He pressure for engine start. No restart.	0	2	0	0	2

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Table 6. (Cont'd)

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FAILURE ANALYSIS CHART FOR: J-2 ENGINE SYSTEM (continued)

SYSTEM: e) GH_2 Start and Tank Pressurization Subsystem.
f) Miscellaneous Engine Subsystems.

COMPONENT	FIND NUMBER	COMPONENT FAILURE MODE	REFERENCE NUMBER	EFFECT OF COMPONENT FAILURE MODE	CHILL DOWN	FAILURE PROBABILITY ASSIGNABLE TO EACH OPERATING PHASE: START	RUN	SHUT DOWN S-II	SHUT DOWN S-IVB
Vent port relief valve (high pressure).	46	Fails open.		No engine start.	0	1	0	0	1
Low pressure relief valve.	47	Fails open.		No engine start.	0	1	0	0	1
Roughing regulator.	48	Fails high.		Redundant with relief valves.		0	0	0	0
		Fails low.		Performance loss.	0	1	2	0	0
4 He check valves.	49	Fails open.			0	0	4	0	0
e) GH_2 Start and LH_2 Tank Pressurization Subsystem:									
Chamber gas filter.	50	Fails.		Contamination.	0	0	1	0	0
Check valves (two).	51	Fails.		Loss of start.	0	1	0	0	1
Pressure switch.	52	Fails when required.		Prevents restart.	0	0	0	0	2
		Open when not required.		Redundant.					
Start Tank Vent and Relief Valve.	53	Fails closed.		Overpressurization of GH_2 start tank, may cause rupture.	0	0	1	0	0
		Fails open.		Loss of restart.	0	0	0	0	1
Start Tank discharge valve (SL, G, Pn, N. C.)	54	Fails to open for start.		Fuel turbine fails to start.		5	0	0	0
		Fails open after start		GG combustion products on discharge valve puppet.	0	0	0	0	1
Start Tank discharge solenoid control valve.	55	Fails to open.		Prevents start cycle.	0	1	0	0	1
		Fails to close.		Prevents restart.	0	1	0	0	1
f) Misc. Engine Subsystems:									
Main stage O. K. pressure switch	56	Fails when required.		No mainstage signal (SSD).	0	4	0	0	0
		Fails when not req'd.		Shuts down engine in error.	0	0	2	0	2

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Table 6. (Cont'd)

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FAILURE ANALYSIS CHART FOR: J-2 ENGINE SYSTEM (continued).

SYSTEM: f) Miscellaneous Engine Subsystems

COMPONENT	FIND NUMBER	COMPONENT FAILURE MODE	REFERENCE NUMBER	EFFECT OF COMPONENT FAILURE MODE	CHILL DOWN	FAILURE PROBABILITY ASSIGNABLE TO EACH OPERATING PHASE: START	RUN	SHUT DOWN: S-II	SHUT DOWN: S-IV B
Tubes, ducts, fittings.	57	All failures.		Some redundant pairs, minor leaks.	1	1	4	0	1
				Fires, explosions.	0	0	(2)	0	0
Elec. Cables, fittings.	58	Failures		(SSD)	0	0	2	0	0
Thrust Chamber	59	Burn thru		(SSD)	2	2	13	0	0
		Combustion instability		Fires, explosions.	(1)	5	(12)	0	0
				Σq	(4)/8	(5)/79	(27)/88	(0)/7	(4)/45

Single J-2 Engine p_{eo} = .9782

Single J-2 TVC p_T = .9970

S-II Stage, Engines and TVC

$\overline{P}_{5,4}\begin{pmatrix}0\\0\end{pmatrix}$ = .890 (N. E. O. C.)

$\overline{P}_{5,4}\begin{pmatrix}1\\1\end{pmatrix}$ = .972 (S. E. O. C.)

for I_F = 85%

Sensor Reliability $S = 1 - 1.25\,(1 - p_{eo})$

where:

( ) indicates catastrophic failure mode

SSD Safe Engine Shut Down

F. O. Fails Open

c/o Cut Off

T/C Thrust Chamber

Valve Code:

SL Spring Loaded

P Poppet

G Gate

VF Variable Flow

Sol. Solenoid

Sq. Squibb Actuated

Pn Pneumatic Operated

Hy. Hydraulic Operated

SM Servo Motor Operated

NO Normally Open

NC Normally Closed

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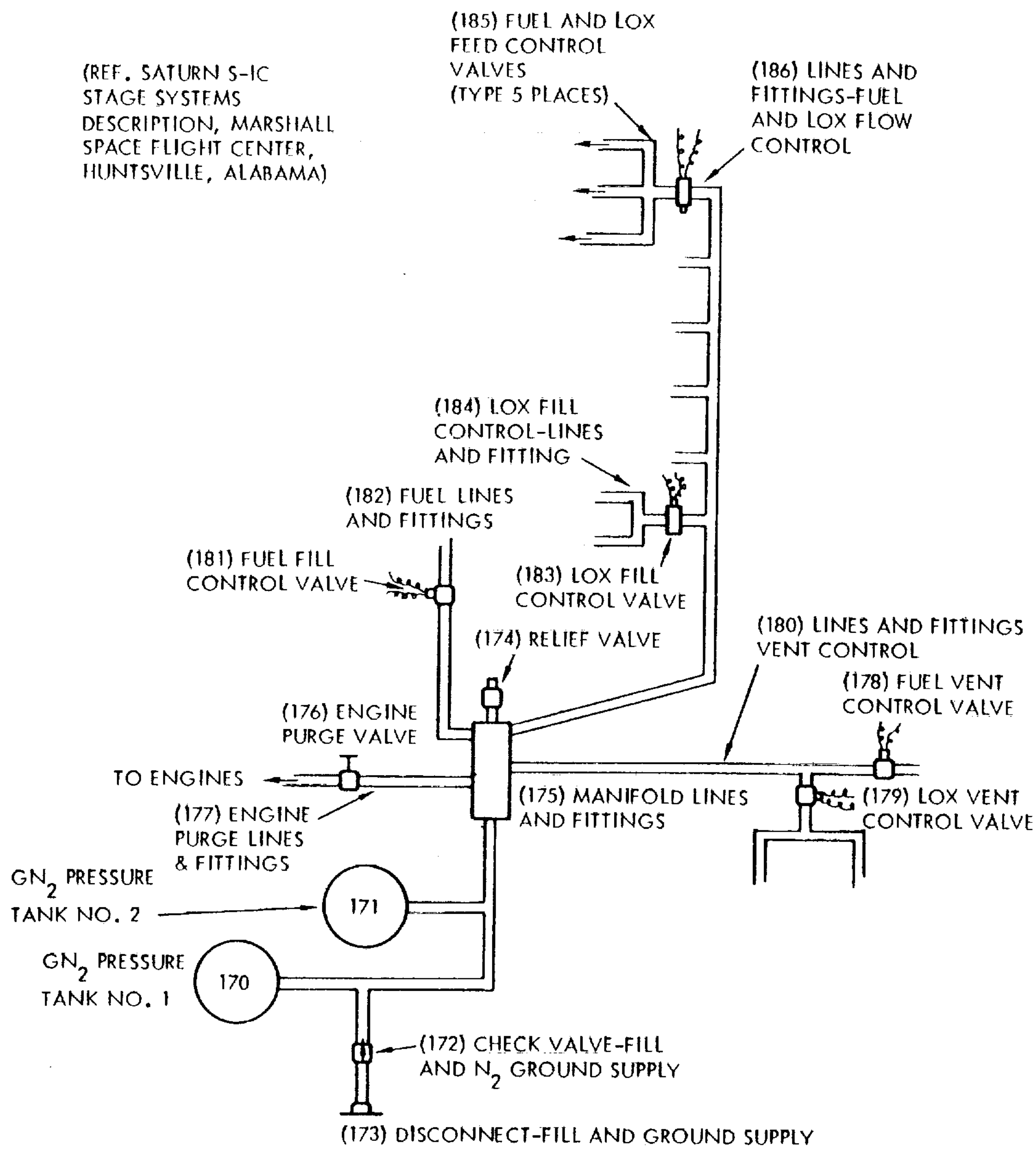

Figure 8. S-IC stage control pressure system of Saturn V vehicle

Table 7.

FAILURE ANALYSIS CHART (SHORT FORM) FOR: S-IC Stage of Saturn V Vehicle

SYSTEM Control Pressure System
State of the Art Reliability Estimate

SYSTEM FAILURE MODES:
0. No Failure
1. ALL ENGINES FAIL
2. SINGLE ENGINE FAILURE
3. GUIDANCE FAILURE
4. CATASTROPHIC EXPLOSION

COMPONENT	FIND NUMBER	COMPONENT FAILURE MODE	REFERENCE NUMBER	EFFECT OF COMPONENT FAILURE MODE	ULTIMATE SYSTEM FAILURE MODE	FAILURE PROBABILITY ASSIGNABLE TO EACH OPERATING PHASE: START	RUN	SHUT DOWN
GN_2 pressure tank No. 1	170	Rupture or excessive leakage	1		1		1.0	
GN_2 pressure tank No. 2	171	Rupture or excessive leakage	2		1		1.0	
Check valve - fill and N_2 ground supply	172	Fail open Fail closed	3 4		1 0		.9999 .9999	
GN_2 disconnect - fill and ground supply	173	Fail open Fail closed	5 6		1 0		1.0 1.0	
Manifold relief valve	174	Fail open Fail closed	7 8		1 4		.9999 .9999	
Manifold lines and fittings	175	Rupture or excessive leakage	9		1		.9997	
Engine purge valve	176	Fail open Fail closed	10 11		1 0		1.0 1.0	
Engine purge lines and fittings	177	Rupture of excessive leakage	12		1		.9998	
Fuel vent control valve	178	Fails open Fails closed	13 14	 Redundant	1 4		.9999 .9999	
LOX vent control valve	179	Fails open Fails closed	15 16	 Redundant	1 4		.9999 .9999	
Lines and fittings - vent control	180	Rupture or excessive leakage	17		0		.9997	
Fuel fill control valve	181	Fails open Fails closed	18 19		2 0		.9999 .9999	
Fuel fill lines and fittings	182	Rupture or excessive leakage	20		0		.9997	
LOX fill control valves	183	Fails open Fails closed	21 22		0 1		.9999 .9999	
LOX fill control lines and fittings	184	Rupture or excessive leakage	23		0		.9997	
Fuel and LOX feed control valves (any of five)	185	Fails open Fails closed	24 25		1 3		.9999 .9999	
Fuel and LOX control lines and fittings	186	Rupture or excessive leakage	26		1		.9997	

SYSTEM RELIABILITY = .9981

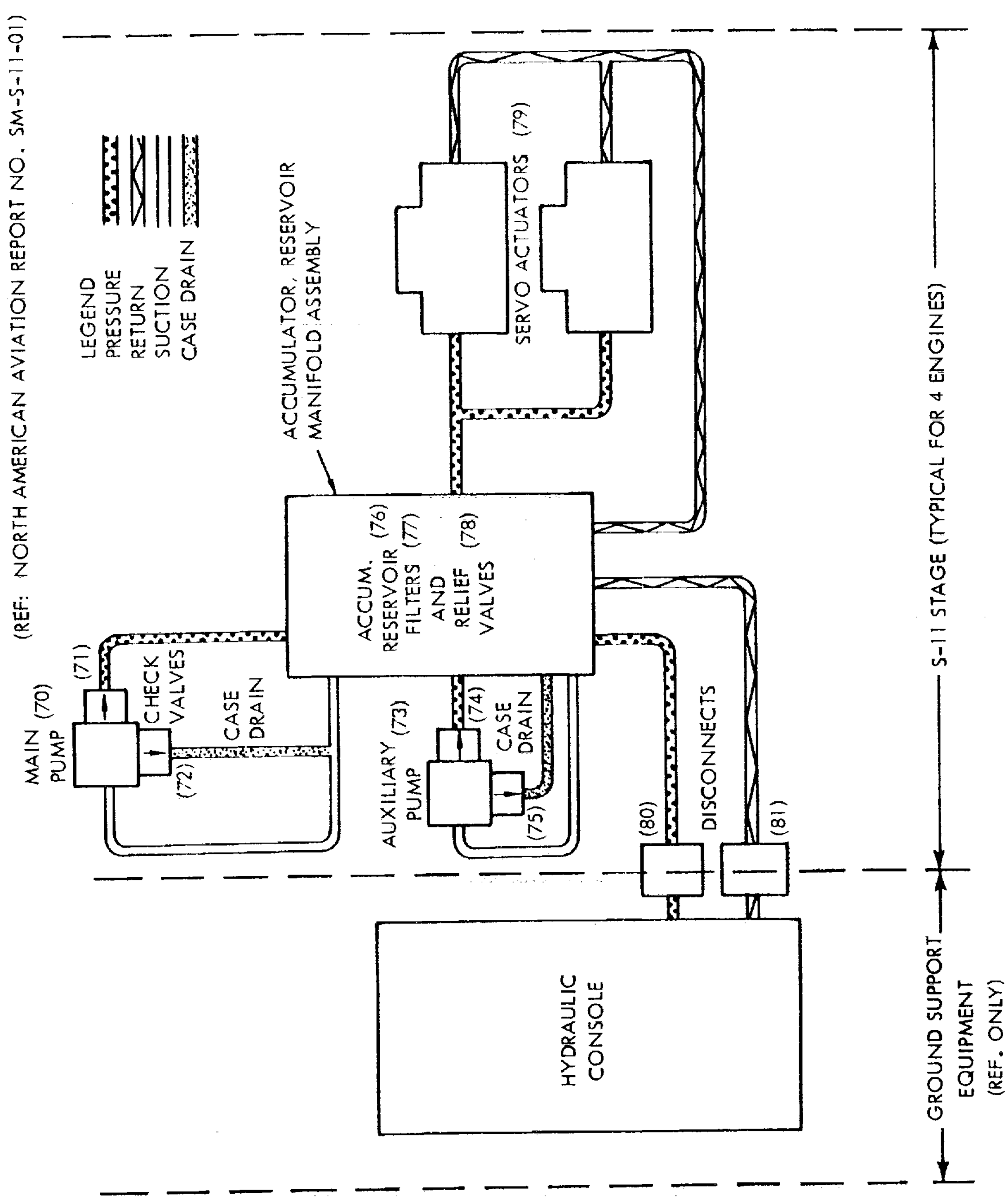

Figure 9. S-II stage hydraulic system

Table 8.

FAILURE ANALYSIS CHART (SHORT FORM) FOR: S-II STAGE OF SATURN V VEHICLE

SYSTEM: Hydraulic
Single Engine Control Subsystem
STATE-OF-THE-ART RELIABILITY ESTIMATE

SYSTEM FAILURE MODES:
0. NO FAILURE
1. ALL ENGINES FAIL
2. SINGLE ENGINE FAILURE
3. GUIDANCE FAILURE
4. CATASTROPHIC EXPLOSION

COMPONENT	FIND NUMBER	COMPONENT FAILURE MODE	REFERENCE NUMBER	EFFECT OF COMPONENT FAILURE MODE	ULTIMATE SYSTEM FAILURE MODE	FAILURE PROBABILITY ASSIGNABLE TO EACH OPERATING PHASE (X 10^{-4}) START	RUN	SHUT DOWN
Main Pump	70	Mechanical Failure.	1		3		12	
Main Pump High Pressure Check Valve.	71	Fails open.	2		3		1	
		Fails closed.	3		3		1	
Main Pump Case Drain Check Valve.	72	Fails open.	4		0		1	
		Fails closed.	5		3		1	
Auxiliary Pump and Motor.	73	Mechanical failure.	6		0		12	
Auxiliary Pump High Pressure Check Valve.	74	Fails open.	7		0		1	
		Fails closed.	8		0		1	
Auxiliary Pump Case Drain Check Valve.	75	Fails open.	9		0		1	
		Fails closed.	10		0		1	
Accumulator-Reservoir Assembly.	76	Rupture or Leak Excessively.	11		3		2	
Filters in High Pressure Lines (Either of two).	77	Element plugs.	12		3		(2)1	
		Element ruptures.	13		0		0	
Relief Valves in High Pressure Lines (Either of two).	78	Fails open.	14		3		(2)1	
		Fails closed.	15		0		(2)1	
Servo Actuator Assemblies (Either of two).	79	Mechanical failure, rupture or leak excessively.	16		3		(2)2	
High Pressure Lines and Fittings.		Rupture or leak excessively.	17		3		3	
Low Pressure Lines and Fittings.		Rupture or leak excessively.	18		3		2	
Ground Pressure Line Disconnect Assembly.	80	Fails open.	19		3		0	
		Fails closed.	20		0		0	
Ground Return Line Disconnect Assembly.	81	Fails open.	21		3		0	
		Fails closed.	22		0		0	
					TOTAL		30	
SINGLE ENGINE HYDRAULIC SYSTEM RELIABILITY				= .9970				

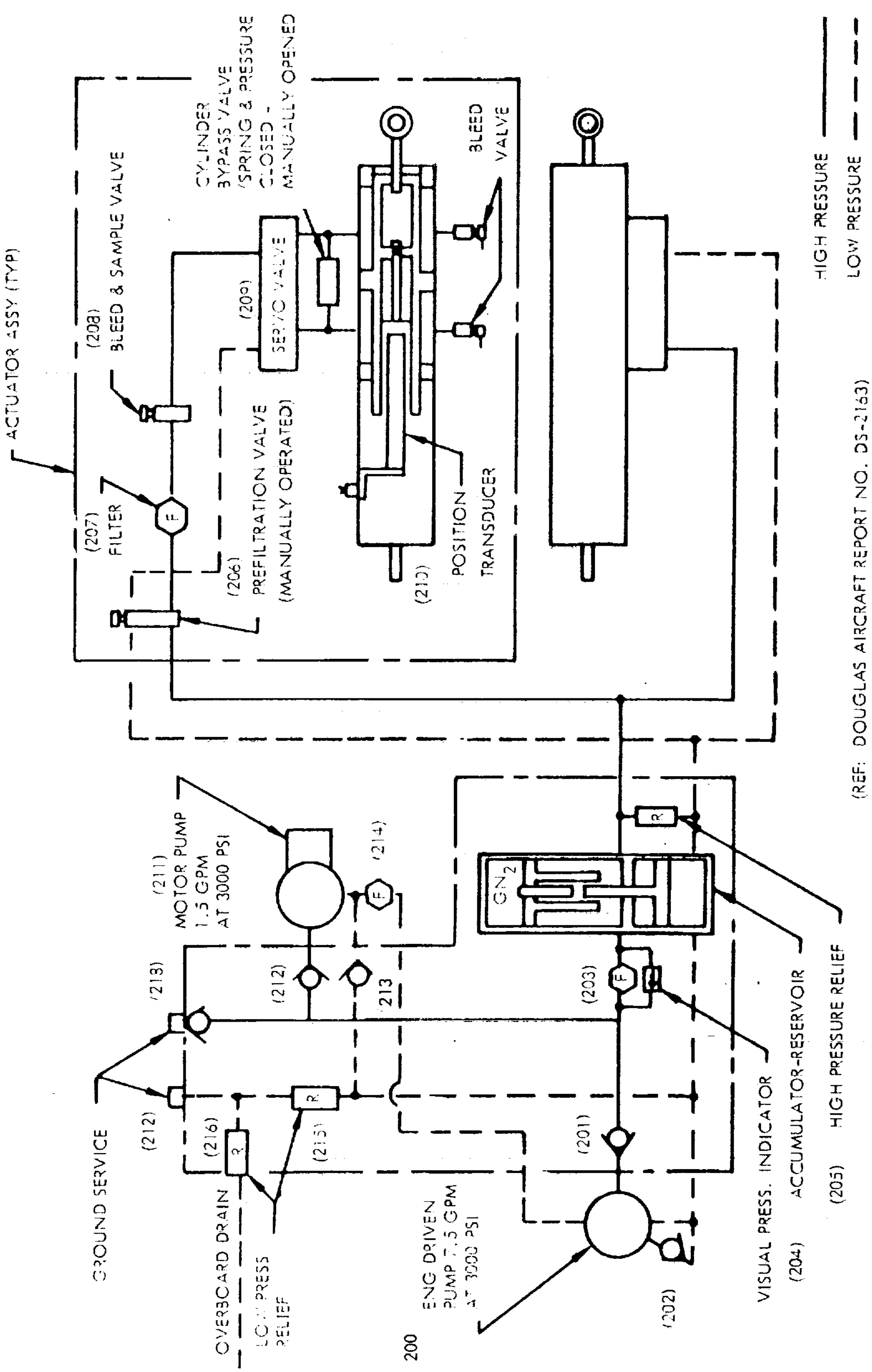

Figure 10. S-IVB stage hydraulic system

Table 9.

FAILURE ANALYSIS CHART (SHORT FORM) FOR: S-IVB STAGE OF SATURN V VEHICLE

SYSTEM: Hydraulic
Single Engine Control Subsystem
State-of-the-Art Reliability Estimate

SYSTEM FAILURE MODES:
0. NO FAILURE
1. ALL ENGINES FAIL
2. SINGLE ENGINE FAILURE
3. GUIDANCE FAILURE
4. CATASTROPHIC EXPLOSION

COMPONENT	FIND NUMBER	COMPONENT FAILURE MODE	REFERENCE NUMBER	EFFECT OF COMPONENT FAILURE MODE	ULTIMATE SYSTEM FAILURE MODE	FAILURE PROBABILITY ASSIGNABLE TO EACH OPERATING PHASE ($X 10^{-4}$) START	RUN	SHUT DOWN
Engine Driven Main Pump	200	Mechanical failure.	1		3		12	
Main Pump High Pressure Line Check Valve	201	Fails open.	2		3		1	
		Fails closed.	3		3		1	
Main Pump Case Drain Line Check Valve	202	Fails open.	4		3		1	
		Fails closed.	5		3		1	
High Pressure Filter	203	Element plugs.	6		3		1	
		Element ruptures.	7		0		0	
Accumulator-Reservoir Assembly	204	Ruptures or leaks excessively.	8		3		2	
High Pressure Relief Valve	205	Fails open.	9		3		1	
		Fails closed.	10		0		1	
Actuator Assembly Prefiltration Valve (Either of two)	206	Fails open.	11		0		1	
		Fails closed	12		3		1	
Actuator Assembly Filter (Either of two)	207	Element plugs.	13		3		(2)1	
		Element Ruptures.	14		0		0	
Actuator Assembly Bleed & Sample Valve (Either of two)	208	Fails open.	15		3		(2)1	
		Fails closed.	16		3		(2)1	
Actuator Assembly Servo Valve (Either of two)	209	Electrical or mechanical failure.	17		3		(2)5	
Actuator Piston, Engine Linkage, and Feedback Transducer (Either of two)	210	Mechanical or electrical failure.	18		3		(2)2	
High Pressure Lines and Fittings		Rupture or leak excessively.	19		3		3	
Low Pressure Lines and Fittings		Rupture or leak excessively.	20		3		2	
Electric Motor Driven Aux. Pump & Motor	211	Electrical or mechanical failure.	21		3		12	
Auxiliary Pump High Pressure Line Check Valve	212	Fails open.	22		0		1	
		Fails closed.	23		3		1	
Auxiliary Pump Low Pressure Line Check Valve	213	Fails open.	24		3		1	
		Fails closed.	25		0		1	

Table 9. (Cont'd)

FAILURE ANALYSIS CHART (SHORT FORM) FOR: S-IVB STAGE OF SATURN V VEHICLE

SYSTEM: Hydraulic
Single Engine Control Subsystem
State-of-the-Art Reliability Estimate

SYSTEM FAILURE MODES:
0. NO FAILURES
1. ALL ENGINES FAIL
2. SINGLE ENGINE FAILURE
3. GUIDANCE FAILURE
4. CATASTROPHIC EXPLOSION

COMPONENT	FIND NUMBER	COMPONENT FAILURE MODE	REFERENCE NUMBER	EFFECT OF COMPONENT FAILURE MODE	ULTIMATE SYSTEM FAILURE MODE	FAILURE PROBABILITY ASSIGNABLE TO EACH OPERATING PHASE (X 10⁻⁴) START	RUN	SHUT DOWN
Auxiliary Pump Low Pressure Line Filter	214	Element plugs.	26		3		1	
		Element ruptures.	27		3		0	
Low Pressure Relief Valve	215	Fails open.	28	Redundant with find number 216 valve.	0		1	
		Fails closed.	29		0		1	
Low Pressure Over-board Drain Relief Valve	216	Fails open.	30	Redundant with find number 215 valve.	0		1	
		Fails closed	31		0		1	
Low Pressure Ground Service Disconnect	217	Ruptures or leaks excessively.	32		3		0	
High Pressure Ground Service Disconnect and Check Valve	218	Fails open in combination.	33	Disconnect and valve are redundant in flight.	3		0	
		Fails closed (valve only).	34		0		0	
					TOTAL		61	

S-IV B STAGE HYDRAULIC SYSTEM RELIABILITY = .9939

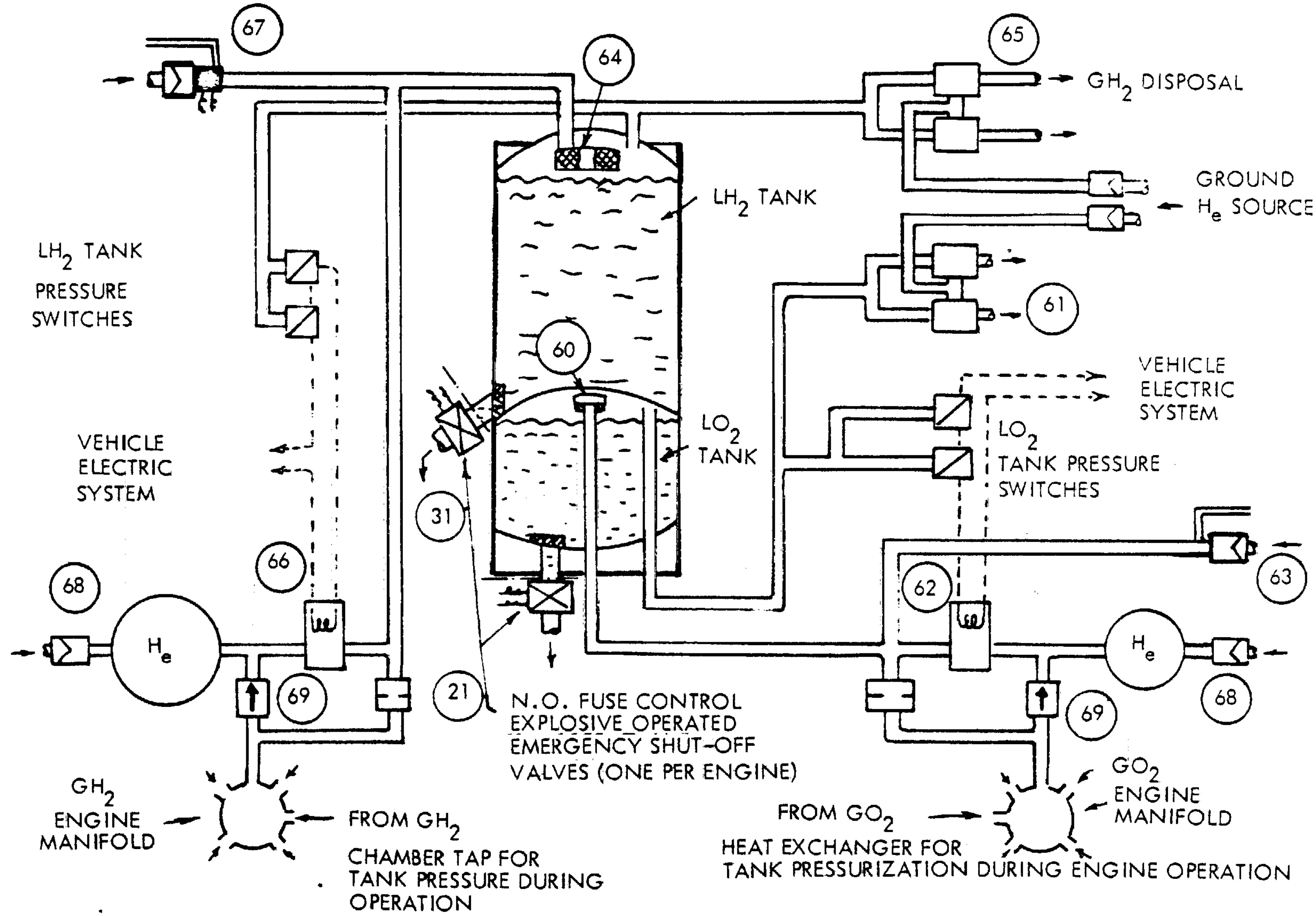

Figure 11. Simplified schematic for engine tank and propellant feed system for S-II and S-IVB

Table 10.

FAILURE ANALYSIS CHART (SHORT FORM) FOR: S-II and S-IV B Stages of Saturn V Vehicle

SYSTEM: Tank and Propellant for J-2 Engine

STATE-OF-THE-ART RELIABILITY ESTIMATE

COMPONENT	FIND NUMBER	COMPONENT FAILURE MODE	REFERENCE NUMBER	EFFECT OF COMPONENT FAILURE MODE	P Chill Down	FAILURE PROBABILITY ASSIGNABLE TO EACH OPERATING PHASE: START	RUN	SHUT DOWN S-II	SHUT DOWN S-IV B
GO_2 Diffuser	60	Clogg, contamination.			0	0	1	0	0
LO_2 Tank vent valves(2)	61	Fails closed		Redundant.	0	0	0	0	0
		Fails open.		Slow leak, possible performance loss.	0	0	1	0	0
LO_2 Tank Pressurization solenoid valve.	62	Fails open.		Lack of pressurization.	3	1	1	0	1
		Fails closed		" "	3	1	1	0	1
LO_2 Insert.Disconnect Fill Drain & Purge.	63	Leaks,		Loss of tank purge.	0	0	1	0	0
GH_2 Diffuser.	64	Clogg, contain.			0	0	1	0	0
LH_2 Tank Vent Valves (2)	65	Fails closed.		Redundant.					
		Fails open.		Slow leak, possible performance loss.	0	0	1	0	0
LH_2 Tank Pressurization solenoid valve.	66	Fails open.		Lack of pressurization	3	1	1	0	1
		Fails closed.		" " "	3	1	1	0	1
LH_2 Inserting Disconnect, Fill Drain and Purge.	67	Leaks.		Loss of tank purge.	0	0	1	0	0
Helium Receiver Tanks, fill and disconnects (2).	68	Leaks.		Loss of tank pressure	0	0	1	0	0
He Check Valves	69	Leaks.		Loss of tank pressure	0	0	1	0	0
Emergency Shutoff valves - 2 per engine. (LO_2, LH_2)	21, 31	(Included with engines)							
				p, TOTAL =	12	4	12	0	4
				P_T = .9972, one start					
				P_T = .9940, two starts					

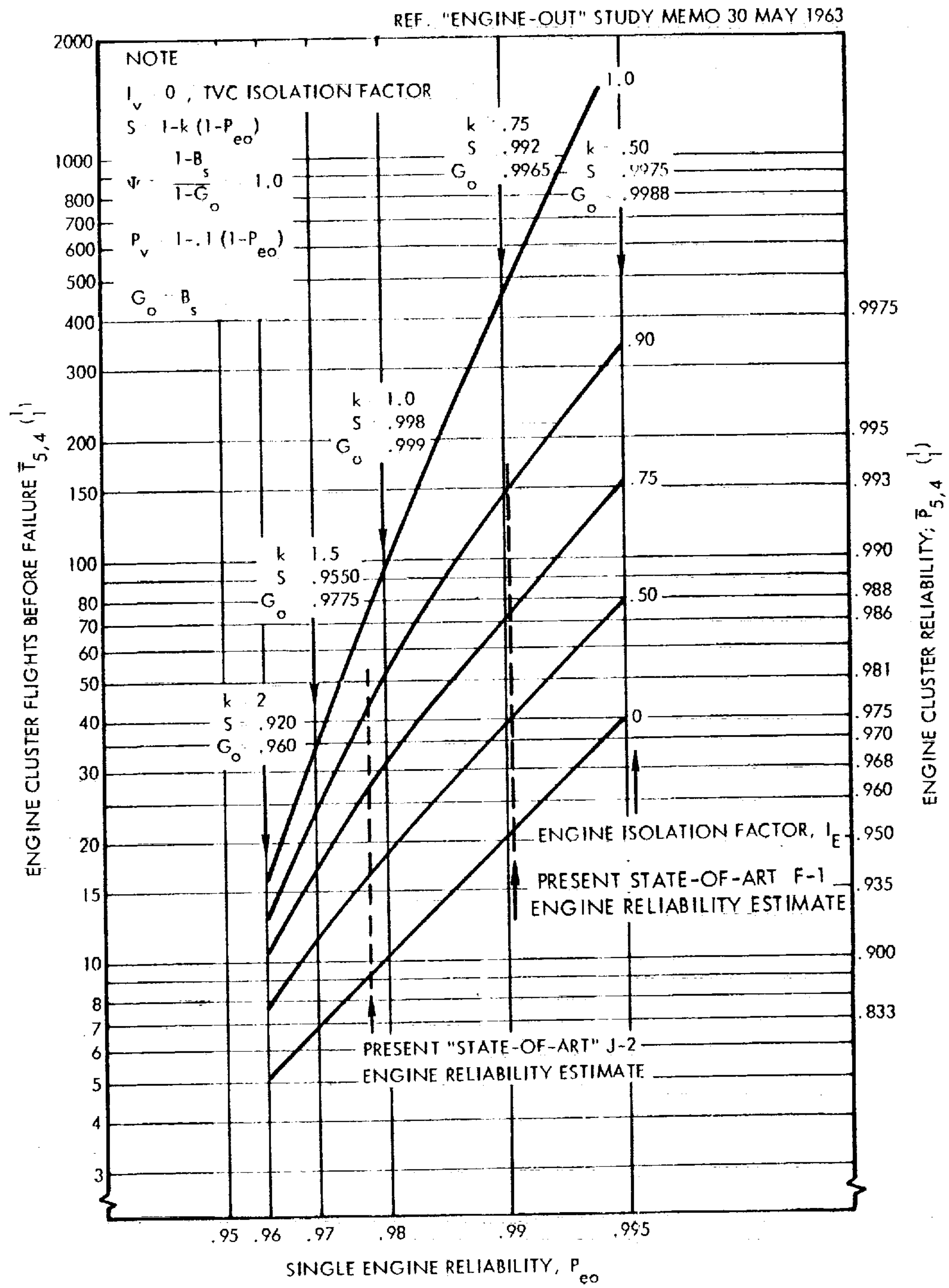

Figure 12. Reliability curves of S-I and S-II stages, engine cluster with five engines, four with TVC

SECTION IV
SUMMARY OF RELIABILITY ESTIMATES

STATE-OF-ART RELIABILITY ESTIMATE

The following listing is a summary of the reliability estimates for the various equipment systems associated with the Saturn V propulsion systems.

1. F-1 Engine Reliability (with hold-down) is .9902.
2. F-1 Hydraulic (TVC) Reliability is .9987.
3. S-IC Stage Fuel System Reliability is .9956.
4. S-IC Stage Oxidizer System Reliability is .9931.
5. S-IC Stage Control Pressure System Reliability is .9981.
6. J-2 Engine Reliability for one (in Flight) start is .9782.
7. J-2 TVC Reliability for one start is .9970.
8. J-2 TVC Reliability for two starts is .9936.
9. J-2 Tank System Reliability for one start is .9972.
10. J-2 Tank System Reliability for two starts is .9940.
11. The S-IC Stage Reliability for five engines, four TVCs, and supporting systems is .933 (for NEOC).
12. The S-IC Stage Reliability for same as item eleven above, but for SEOC is .969 (Isolation factor = 75%).
13. The S-II Stage Reliability for five engines, four TVCs and supporting systems for one start is .880 (for NEOC).
14. The S-II Stage Reliability for same as item thirteen above, but for SEOC is .970 (Isolation factor = 75%).
15. The S-IVB Engine Reliability, one engine for one restart is .9522.
16. The S-IVB Propulsion Stage Reliability, one engine, one TVC (Hydraulic), and one tank system, for one restart (two starts) is .938.

SATURN V PROPULSION SYSTEM RELIABILITY ESTIMATE CALCULATIONS

The following is a brief summary of some of the calculated results of this study, based on the mathematical techniques presented in TEMPO report RM 63TMP-24 relating to the Saturn I revised propulsion system reliability analysis.[3] Refer to the List of Symbols on the last page of this section for definition of symbols used in this summary.

Simplified S-II and S-IVB Engine Tanks and Propellant Feed System

$q_{T1} = 12$ (chill down) ; $q^*_{T2} = 0$

$q_{T2} = 4$ (start) ; $q^*_{T2} = 0$

$q_{T3} = 12$ (run) ; $q^*_{T3} = 0$

$q_{T4} = 0$ (stop) ; $q^*_{T5} = 0$

hence for the S-II stages,

$\bar{q}_{TO} = (12 + 16) = 28$

$\bar{P}_{TO} = .9972$; Reliability of tank system for one in-flight start,

and for the S-IVB stage,

$\bar{q}_{TO} = (12 + 20 + 12 + 16) = 60$

$\bar{P}_{TO} = .9940$; Reliability of tank system for two in-flight starts.

S-II Propulsion System Reliability

With five J-2 engines, 1 tank system, 4 TVCs.

1. No Engine Out Capability (N.E.O.C.)

a. Single Engine Reliability

$$q_{e0} = (q_{e1} + q_{e2} + q_{e3} + q_{e4}) \quad (1)$$

$q_{e1} = (4 + 8) = 12$, chill down (first figure in parenthesis is the catastrophic failure mode)

$q^*_{e1} = 4$

$q_{e2} = (5 + 79) = 84$, start

$q^*_{e2} = 5$

$q_{e3} = (27 + 88) = 115$, run

$q^*_{e3} = 27$

$q_{e4} = (0 + 7) = 7$, stop

$q^*_{e4} = 0$

therefore,

$q_{e0} = 218$; $p_{e0} = .9782$, Single engine reliability for all failures

$q^*_{e0} = 36$; $p^*_{e0} = .9964$, Single engine reliability against catastrophic failure

b. Cluster of Five Engines

With 4 TVCs single TVC estimated reliability for S-II stage is:

$p_v = .9970$; $q_v = 30$

$$\overline{P}_{5,4}\begin{pmatrix}0\\0\end{pmatrix} = 1 - (q_{e0} + q_v)^4 \; (1 - q_{e0}) \tag{2}$$

$$= \left[1 - (218 + 30)\right]^4 \; (.9782)$$

hence,

$P_{5,4}\begin{pmatrix}0\\0\end{pmatrix} = .890$, for S-II propulsion (less tanks).

c. Cluster of Five Engines and Engine Shutdown (S.S.D.) Capability

Of the 36 failures resulting in catastrophic failures, it is assumed that about half of these could be reduced to safe shutdown of engine, if sensor system were used. Thus, the isolation factor is estimated to be:

$$I_F \approx \left(\frac{q_{e0} - .50\, q^*_{e0}}{q_{e0} + .50\, q^*_{e0}}\right) \tag{3}$$

$$= (200/236) = .85$$

1) For $I_F = .85$, Engine and TVC cluster reliability for safe shutdown, (but not S.E.O.C.) is:

$\overline{P}_{5,4} \begin{pmatrix} 1 \\ 1 \end{pmatrix} = .9720$, for S.S.D., Engines and TVC.

2) Propulsion System, S-II S.S.D. reliability including tank system is:

$R_P = (.972)(.9972) = .9692$

which permits alternate mission, safety, etc.

3) Propulsion System, S-II, mission success reliability is:

$R_P = (.890)(.9972) = .8880$ (N.E.O.C.)

and

$R_P^* = (.9964)^5 = .9822$ (N.E.O.C.) reliability of engine cluster against catastrophic failure.

2. Single Engine and Single TVC Out Capability

Numerically, this is the same as R_P^* for S.S.D., thus, the cluster propulsion reliability for mission success is:

$R_P = .970$ (S.E.O.C.) .

S-IVB Propulsion System Reliability

1. One-J-2 Engine and One-TVC; for one restart (two starts).

$$q_{e0} = (2q_{e1} + 2q_{e2} + 2q_{e3} + q_{e5} + q_{e4}) \qquad (4)$$

where

$q_{e5} = (4 + 45) = 49$ (shutdown, restart required)

$q_{e0} = 478$ and $q_{e0}^* = 76$

$p_{e0} = .9522$, p_{e0}^* $.9924$.

2. S-IVB "TVC" system reliability was calculated for two complete runs and a coasting period:

$p_v = .9939$

3. The S-IVB engine tank and propellant feed system reliability estimates for the two chill downs, two starts, two runs, one shutdown and one stop is:

$$q_T = .9940.$$

4. The total S-IVB propulsion stage reliability for the engine, TVC, tank and feed system is:

$$P_{1,1} = (.9522)\,(.9939)\,(.9940) = .938.$$

LIST OF SYMBOLS

P_{e0}	Total engine reliability
P_{e1}	Engine reliability, during chill down
P_{e2}	Engine reliability, during start
P_{e3}	Engine reliability, during run
P_{e4}	Engine reliability, at stop (no restart capability)
P_{e5}	Engine reliability, at shutdown (for restart capability)
q	Engine unreliability, (probability of failure, usually given in ten thousandths)
p*	Reliability in catastrophic failure mode ($p = 1 - q \times 10^{-4}$)
P_{TO}	Total tank system reliability, etc.
N.E.O.C.	No engine out capability
S.E.O.C.	Single engine out capability
S.S.D.	Safe engine shutdown
S	Sensor reliability, all failure modes
G_S	$(1 - G_o)$ probability of shutting down good engine
G_o	$(1 - G_S)$ probability of not shutting down good engine
B_S	Probability of shutting down a bad engine
B_o	$(1 - B_S)$, probability of not shutting down a bad engine
Ψ	(B_o/G_S), probability ratio of two engine sensor failure modes.

$\bar{\bar{P}}_{m,n} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$	Cluster reliability for m engines, n TVCs and one out capability for each
I_E	Isolation factor for engine
I_V	Isolation factor for TVC system.

REFERENCES

1. North American Aviation, Inc., Rocketdyne Division. H-1 Engine Reliability Status: Catalogued as General Electric Company, TEMPO, TMP-13820. (CONFIDENTIAL).

2. North American Aviation, Inc., Rocketdyne Division. Engine Test Stand Data, REM-1181-1544, p 4. June 1961.

3. General Electric Company, TEMPO. Saturn I Revised Propulsion System Reliability Analysis, RM 63TMP-24. Santa Barbara, California: April 1963.

BIBLIOGRAPHY

1. North American Aviation, Inc., Rocketdyne Division. Preliminary Engine Data, Rocket Engine Model J-2, R-2825-1. Los Angeles, Calif.: 18 April 1963 (CONFIDENTIAL).

2. North American Aviation, Inc., Rocketdyne Division. F-1 Design Information, R-2823-1. 23 August 1961 (CONFIDENTIAL).

3. North American Aviation, Inc., Rocketdyne Division. Failure Effect Analysis, F-1 Engine Subsystem, RAR-2181-1503.

4. North American Aviation, Inc., Rocketdyne Division. Failure Effect Analysis, J-2 Engine Subsystem, RAR-2181-1504.

5. North American Aviation, Inc., Space and Systems Division. Saturn S-11 General Manual, NASA Support Document, SM-S-11-01. 1 April 1963.

6. Douglas Aircraft Company, Inc., Missile and Space Systems Division. Reliability Mathematical Model Saturn S-IVB Stage, SM-43610. Culver City, Calif.: 15 April 1963.

7. Douglas Aircraft Company, Inc., Missile and Space Systems Division. Model Specification, Saturn S-IVB Stage, DS-2163. 15 February 1963 (CONFIDENTIAL).

8. Marshall Space Flight Center. Saturn S-IC Stage Systems. Huntsville, Ala.: Received May 1963 (CONFIDENTIAL).

9. Marshall Space Flight Center. Saturn V Project Development Plan. 1 April 1963 (CONFIDENTIAL).

10. General Electric Company, TEMPO. Reliability Growth, for Liquid and Solid Rocket Single and Clustered Stages: Material integrated into a study for the Large Launch Vehicle Program Group, (LLVPG). November 1961 (SECRET).